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HYDRAULIC FRACTURING OF SOILS: A LITERATURE REVIEW.(U)
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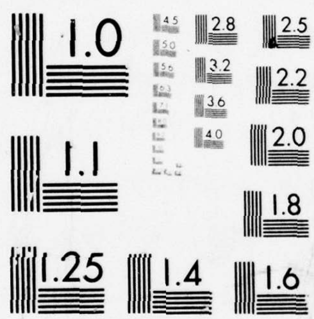
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HYDRAULIC FRACTURING OF SOILS
A LITERATURE REVIEW

by

Roy E. Leach

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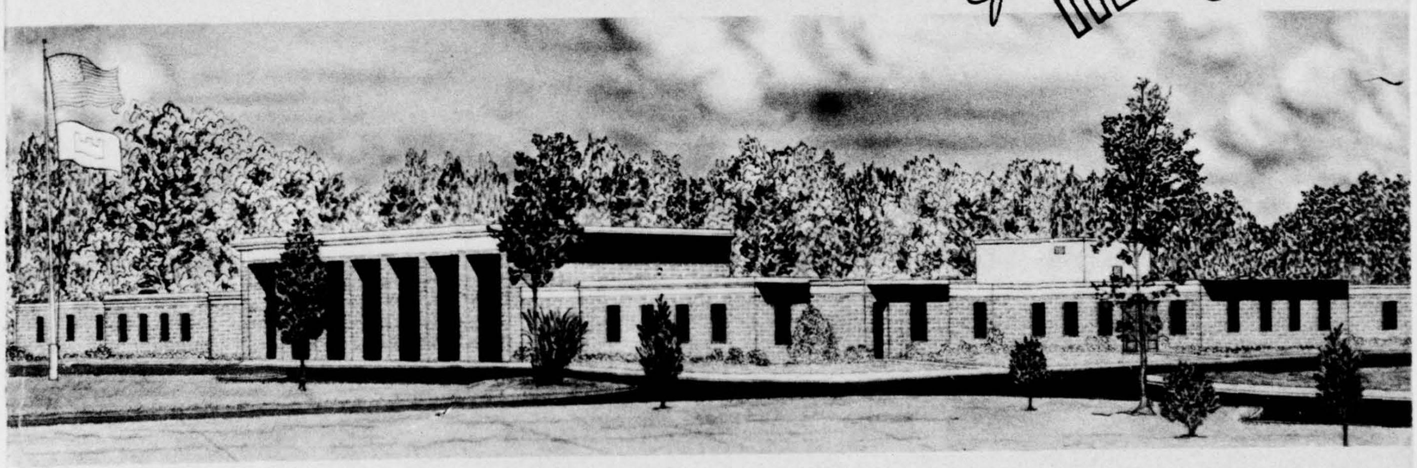
March 1977

Final Report



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New and more detailed analyses are being developed in soil mechanics for earth structure and foundation designs which require a detailed definition of in situ stresses and strains in soils. Although no tests exist that give absolute answers, numerous tests can be used as tools to determine ranges, best case, or worst case. The study reported herein is an overview of one such test or technique, hydraulic fracturing, which is defined as the formation of cracks,

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in soil by the application of hydraulic pressure greater than the minor principal stress at that point.

Hydraulic fracturing, as a technique, has been used for many years by oil companies but up until the last 10 to 15 years this method has not been used extensively to determine stresses in a soil medium. Numerous tests have been conducted in the laboratory and in the field to validate mathematical theories of soil stress with actual data. Laboratory tests have been successful in determining stresses for a controlled test and a controlled sample, but field tests have yet to attain more than fair accuracy under uncontrolled soil conditions.

At present, it is believed that the pressure at which a crack not opens but closes in a decreasing pressure situation more nearly defines the minor principal stress across the crack. As the crack closes there is an abrupt change in flow since there will be no flow in the crack and the permeability of the soil governs. This method eliminates two variables associated with the crack opening process: (1) outward movement of the soil before cracking and (2) irregular flow from the source and in the crack. One other important variable, loading history, affects both methods of determining the ratio of horizontal to vertical effective stress, K_o , for design. For an overconsolidated condition, the minor principal stress would approximate the vertical (overburden) stress instead of the lateral stress, thereby negating obtaining a K_o ratio.

There is evidence presented in a recent (June 1975) ASCE In Situ Measurement Conference that there is disagreement of values obtained by different methods (conventional laboratory, pressuremeter, vane shear, etc.) of determining minor stresses and it is suggested that fracturing is just another tool that helps to define a range of values. While there are reservations concerning hydraulic fracturing as a means for determination of lateral stresses, the technique can still be used for determining in situ total stress and permeability at a point in a cohesive soil.

PREFACE

The investigation reported herein was one phase of a project, "Instrumentation of Embankments and Foundations," sponsored by the Office, Chief of Engineers (OCE) under CWIS 31189. The investigation was conducted by the U. S. Army Engineer Waterways Experiment Station (WES), Soils and Pavements Laboratory (S&PL), during the period July 1974 through March 1975 under CWIS 31189 which was terminated in fiscal year 1975. This report was completed during January-May 1976 as Task 14, Hydraulic Fracturing, under CWIS 31173, "Special Studies for Civil Works Soils Problems."

The investigation was conducted and this report was prepared by Mr. R. E. Leach under the general supervision of Mr. V. H. Torrey III, formerly Chief, Engineering Studies Branch, and Mr. C. L. McAnear, Chief, Soils Mechanics Division. Mr. J. P. Sale was Chief, S&PL. OCE technical monitor for this study was Mr. R. R. W. Beene.

Directors of WES during the investigation and preparation of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

HYDRAULIC FRACTURING OF SOILS; A LITERATURE REVIEW

PART I: INTRODUCTION

Background

1. The development and increasing use of deformation and finite element methods of analysis in soil mechanics have emphasized the need for determining in situ lateral stresses more reliably. Theoretical explanations are available which state that the behavior of soil under loads is dependent on the stress direction. A knowledge of lateral stress or the change of stress provides a valuable tool for the engineer in determining the critical or maximum stress path for use in the stress path design; thus the engineer is able to predict more closely the deformations and local yields occurring around excavations and within earth embankments.

2. The need exists to determine lateral stresses in situ so that the engineer will have available as much data as possible for design before construction, and so that by calculations using data collected currently the safety factor can be checked during and after construction. These lateral stresses can also be related to tensile strains which in turn are important for studying the tensile behavior of stabilized and unstabilized soils.

3. While there are new methods being developed to measure lateral stresses,[1-4] this report consists mainly of a review of the hydraulic fracturing technique. Hydraulic fracturing is simply the formation of cracks in a soil by excessive water pressure. Fracturing occurs when the in situ effective compressive stress (minor principal stress) is reduced to a negative value greater than the tensile strength in the soil. The orientation of the fracture is dependent on and perpendicular to the minor principal stress in isotropic homogeneous soils while certain types of layering can force fracture orientation in others. The

complicated mathematics brought about by changing stress planes before fracture may be simplified by determining stress when hydraulic pressure is reduced and the crack closes, i.e., the minor principal stress equals closure pressure (total stress across the crack). The problem of hydraulic fracturing is complicated, but an attempt is made in this report to discuss the following aspects:

a. The theory of hydraulic fracturing.

b. The assumptions used in the theory.

c. The soil properties used in the theory.

d. The laboratory techniques used.

e. The field in situ techniques used.

Purpose of Study

4. The purpose of this study was to examine the theory of, field and laboratory tests for, and resulting soil properties determined by the hydraulic fracturing technique. Although lateral stresses are the most important aspect of the technique, permeability and grouting pressure information can also be obtained.

PART II: THEORY OF HYDRAULIC FRACTURING

5. Numerous factors and assumptions must be considered in the theoretical solution for the mechanics of hydraulic fracturing in situ. Some of the more significant factors include:[5]

- a. The initial stress and pore pressure conditions.
- b. The changes in stress due to the piezometer installation or other disturbances.
- c. The magnitude and time variation of the pressure head.
- d. The homogeneity and deformation characteristics of the soil.
- e. The geometry of the piezometer tip.

Secondary factors exist such as permeability of the piezometer, hydraulic properties of the tubing, and the presence of air or solubles in the pore water. These are specific problems that vary between sites.

Stress Change Due to Piezometer Placement

6. An analysis of the change in stress due to forcing a piezometer into the soil has been presented by Bjerrum et al. and Hvorslev.[5,6] It is assumed there is no pore pressure buildup and a long vertical cylindrical cavity is slowly expanded under an internal pressure. As the pore pressure, u_p ,* is increased there will be an initial elastic yield; then an incipient plastic yield is attained. At the start of the elastic yield, assuming plane radial strain, changes in effective stress and strains are defined as

$$E \frac{d\mu}{dr} = (1 - \nu^2)\Delta\sigma_r' - \nu(1 + \nu)\Delta\sigma_\theta'$$

and

$$E \frac{\mu}{r} = (1 - \nu^2)\Delta\sigma_\theta' - \nu(1 + \nu)\Delta\sigma_r'$$

---

* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix A).

By assuming a purely frictional soil is deforming plastically at constant volume and by ignoring elastic volume changes, the radial and circumferential effective stresses in the soil adjacent to the piezometer can be mathematically defined as

$$\sigma'_r(a) = (1 + \beta)K_oP'_o$$

and

$$\sigma'_\theta(a) = (1 - \alpha)K_oP'_o$$

where β and α are factors dependent on soil compressibility defined as

$$\beta = \frac{2N}{N + 1}\left[\frac{E}{2K_oP'_o(1 + \nu)}\left(\frac{N + 1}{N - 1}\right)\right]^{(N-1)/2N} - 1$$

and

$$\alpha = 1 - \frac{2}{N + 1}\left[\frac{E}{2K_oP'_o(1 + \nu)}\left(\frac{N + 1}{N - 1}\right)\right]^{(N-1)/2N}$$

where N is the ratio of radial to circumferential effective stress at plastic yield defined as

$$N = \frac{1 + \sin \phi'}{1 - \sin \phi'}$$

Soil compressibility, $E/K_oP'_o(1 + \nu)$, is the major factor affecting α and β (Bjerrum et al.) while each is relatively insensitive to shearing resistance, ϕ'. These equations are used in determining the stress that must be overcome in initiating hydraulic fracturing.

Stress Conditions at Fracture

7. A general solution can be used to determine the head causing hydraulic fracturing or further deformation of the soil surrounding the piezometer. By assuming conditions of equilibrium, axially symmetric

plane polar coordinates, effective stresses, and plane radial strains, equations can be generated mathematically for the effective stresses. If the soil extends a great distance, i.e., no end conditions, the circumferential effective stress is exceeded and radial cracking occurs when the excess head is:

$$\Delta u_c = \left(\frac{1}{\nu} - 1\right)\left[P_t' + (1 - \alpha)K_o P_o'\right]$$

This stress exists if the soil cracks before moving away from the piezometer. It is possible for the soil to move away (blow off) from the piezometer if the radial effective stress reaches zero at an excess head defined by:

$$\Delta u_b = K_o P_o'(1 + \beta)$$

If blow off occurs a new datum of stress is developed thereby creating a new circumferential effective stress. Using the new set of conditions created, the excess head needed for cracking to occur can be defined as:

$$\Delta u_c = (1 - \nu)\left[P_t' + (2 - \alpha + \beta)K_o P_o'\right]$$

8. The preceding equations apply to vertical cracks with lateral (minor principal) stresses less than the vertical stress (overburden pressure). If the lateral stress is larger than the vertical (minor principal) stress horizontal cracking will occur at an excess head defined by:

$$\Delta u_c = P_o'$$

This is based on the assumption that the soil has no tensile strength.

Rate of Flow Conditions After Cracking

9. As shown above, conditions at the moment of fracture are difficult to express mathematically. Another approach[7] is to determine stress at the time when the crack just closes, i.e. when flow abruptly decreases. For the crack to remain open, the source pressure must equal

the total stress across the crack. Head losses are incurred by flow of water in the crack; therefore, the total measured pressure is the pressure needed to form the crack plus the pressure caused by the head losses. By hydraulic theory assuming laminar flow between two plates, a qualitative expression for head loss in the crack can be determined:

$$\Delta u_c = f\left(q_c, L, b^{-3}, \mu_v\right)$$

If it is assumed that the width of the crack is proportional to the excess pressure, $u_p - \sigma_3$, then the rate of flow can be approximated by:

$$q_c \approx (u_p - \sigma_3)^4$$

From this equation it is seen that when σ_3 (total stress across the crack) equals u_p (pore pressure) flow into the crack will be zero. This is an approximation since flow into the soil will continue until flow pressures are equalized. Since there is nonsteady flow from a source such as a piezometer or a crack in the soil, pressure versus flow will not be linear. In a decreasing flow situation, Figure 1, a distinct deviation from this curved line indicates the flow pressure is approaching the minor principal stress and a state of no flow in the crack can be interpreted as the minor principal stress.

Consideration of K_o

10. As stated earlier hydraulic fracturing is a procedure that can be used to determine lateral or minor principal stresses, permeability, and allowable grouting pressures. K_o, the ratio of horizontal to vertical effective stress, is an influencing factor in each of these determinations or is itself determined using the hydraulic fracturing technique.

11. The loading history, both past and present, of a soil under consideration influences the value of K_o and is important if an analysis of existing stress conditions is to be attempted. An approximation

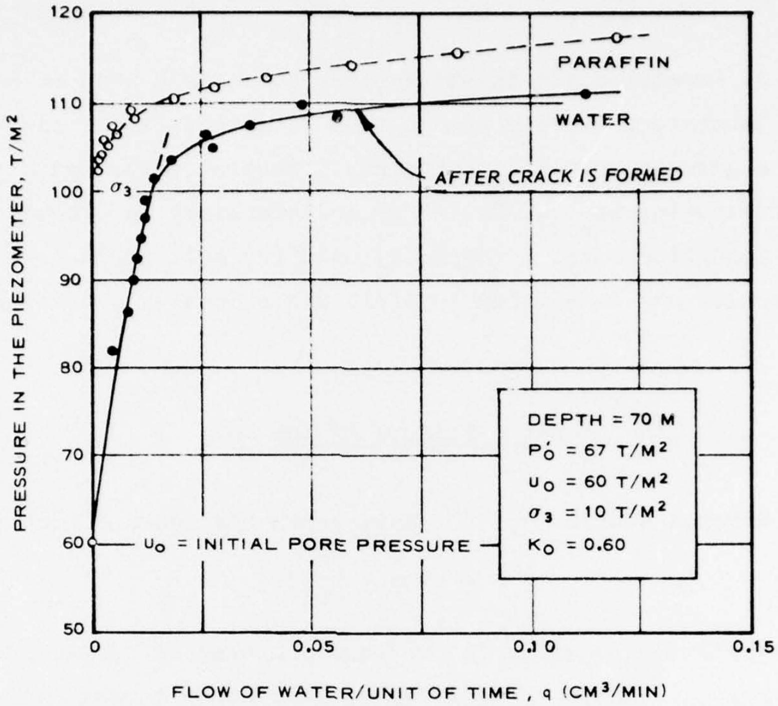


Figure 1. Observed relationships between pressures in the piezometer and rate of flow from the piezometer in falling head tests using both water and paraffin (from Reference 7)

of K_o from Jaky's theoretical approach[8]

$$K_o \approx 1 - \sin \phi'$$

has been established[9,10] as sufficiently accurate for engineering purposes for a wide range of normally consolidated soils, but a normally consolidated condition implies the loading history is known which is often difficult to determine for a field situation.[11] For design purposes a method of checking or determining K_o, such as hydraulic fracturing, is needed. Although a value of stress will be determined by fracturing, it will be a minor principal stress and has a maximum limit equal to the overburden pressure.

PART III: LABORATORY EXPERIMENTS

12. As in most soils investigations there is a need to perform controlled laboratory experiments so that field situations can be analyzed with a greater degree of certainty. Several variables affecting hydraulic fracturing can be duplicated in laboratory conditions--(a) stress conditions, (b) homogeneity, and (c) soil properties--whereby the test results can be applied to field situations as a standard or range.

Tensile Failure of the Soil

13. Several studies[12,13,14] have shown that when effective stress

$$\sigma' = \sigma - u_p$$

becomes sufficiently negative to overcome the tensile force, hydraulic fracturing occurs. Based on this fact a laboratory investigation[15] was conducted to first check the validity of these studies and second to vary the stress conditions and determine the resulting effects. An apparatus (Figure 2) was designed to test a hollow core sample so that different water pressures could be applied at the inner and outer surfaces during tests. Also a cap was used to apply or relieve an axial load on the end of the sample. Four different types of tests were conducted:

Type I. Outward flow was maintained by applying a larger inside than outside pressure while the axial load was reduced until failure occurred.

Type II. Inward flow was maintained by applying a larger outside than inside pressure while the axial load was reduced until failure occurred.

Type III. The outside pressure and axial load were held constant while the inside pressure was increased until failure occurred.

Type IV. The inside and outside pressures were held constant while the axial load was reduced until failure occurred.

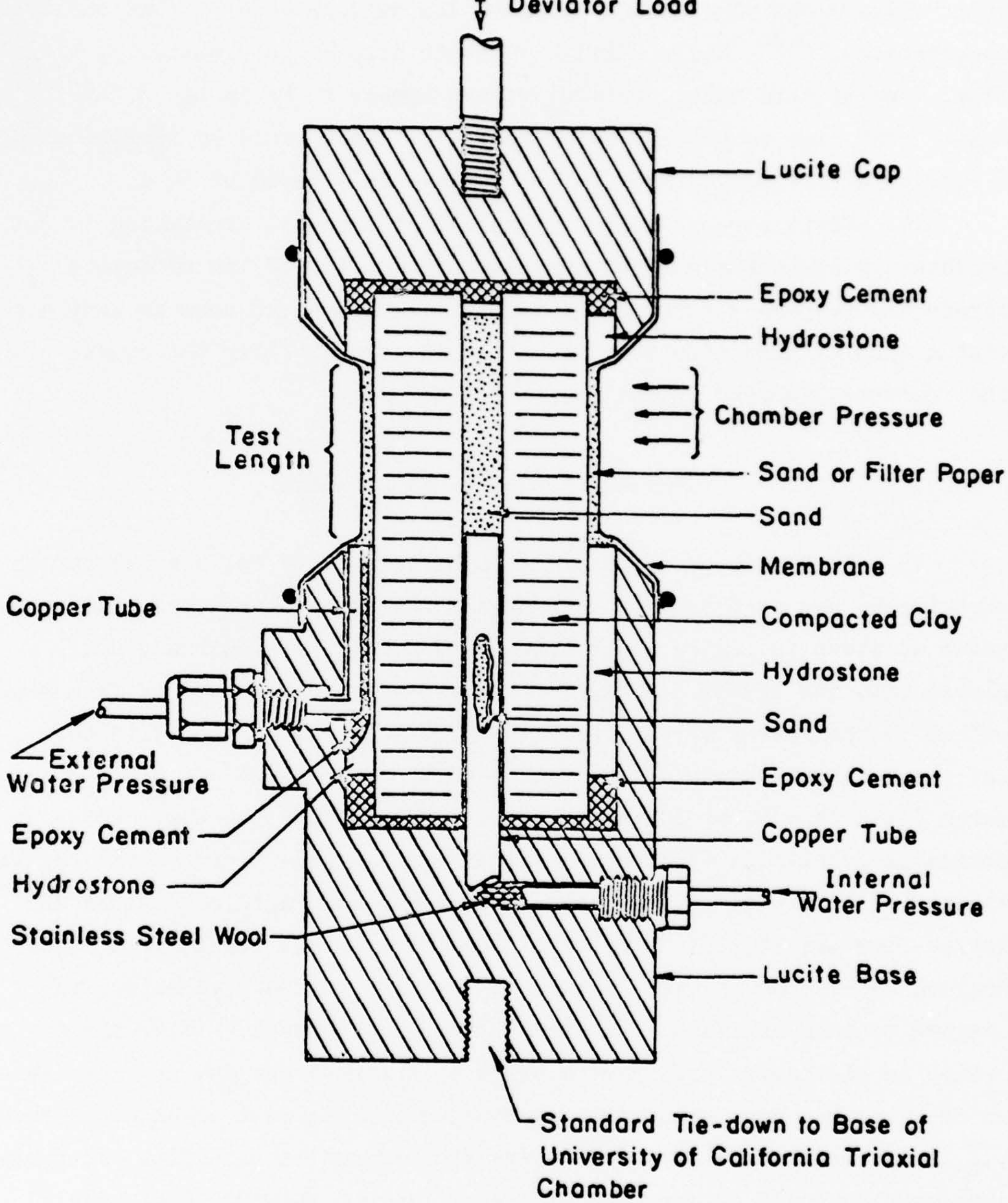


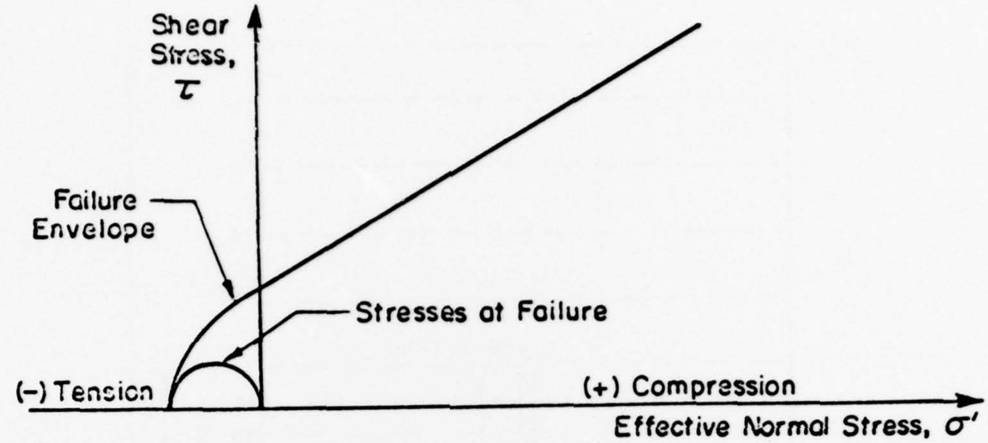
Figure 2. Apparatus for hydraulic fracturing experiments (from Reference 15)

In each case by using Mohr's circles (Figure 3a) it was established that the failure mechanism was hydraulic fracturing (tension failure) and not shear failure and plastic flow (Figure 3b) as suspected by some earlier observations.[13,16] While tensile strength depends on plasticity, grain size, density, and water content, values appear to be in the 0.2-kg/cm^2 range[15] for high compaction water contents. This would be approximately 6 percent of the hydrostatic water pressure at a depth of 30 m.

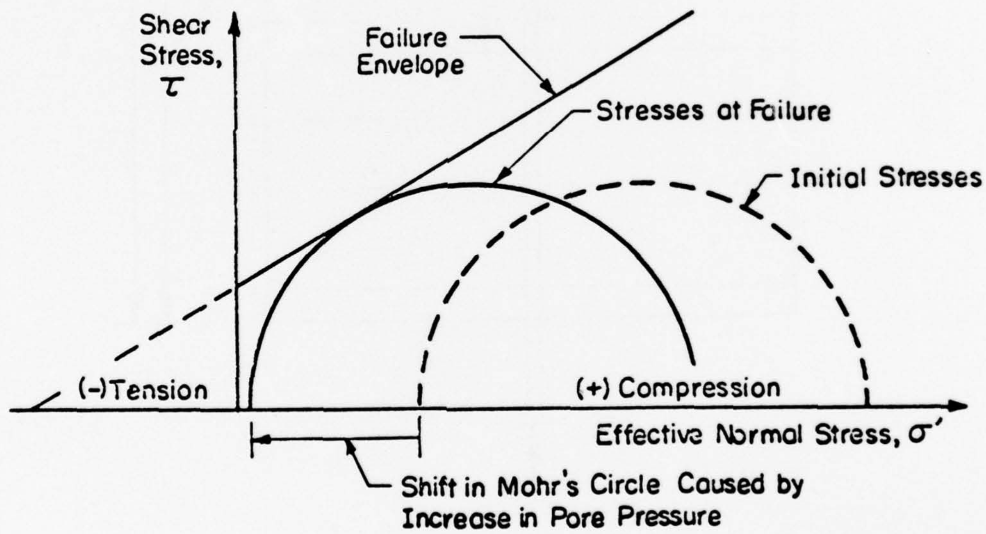
14. Since pore pressure is applied at a point, fracturing is not necessarily instantaneous but may start at a point of low effective stress and propagate through the material. This would seem to indicate that a zone of high effective stress would stop or alter the course of the fracture, thereby preventing total failure.

Bjerrum and Anderson Experiment

15. To try to prove the results of some field tests a laboratory experiment[7] was performed by Bjerrum and Anderson using a triaxial apparatus as shown in Figure 4. A specimen confined by a membrane was placed into the device. A small piezometer was then pushed in from the bottom to the center of the specimen. The specimen was consolidated using a vertical stress of P_o' and a horizontal stress of $0.5\ P_o'$ to match field conditions and was allowed to drain from the top. After consolidation, drainage was stopped and an initial pore pressure reading was taken. At this point the specimen approximated in situ conditions and inward flow was started into the piezometer with a screw control which drained water from a sump. Pressure, measured in the piezometer, increased to some maximum value then started to decrease. After the decrease in piezometer pressure, a bulge in the membrane and an increase in the specimen pore pressure were noticed indicating a crack had formed out to the membrane. Inward flow was stopped and outward flow and pressure were recorded as each was allowed to adjust freely. Again the point at which there was an abrupt decrease in flow was considered to be closure of the crack, or the minor principal stress.



a. Tension failure caused by Type IV test



b. Shear failure caused by increasing pore pressure

Figure 3. Stress conditions at failure (from Reference 15)

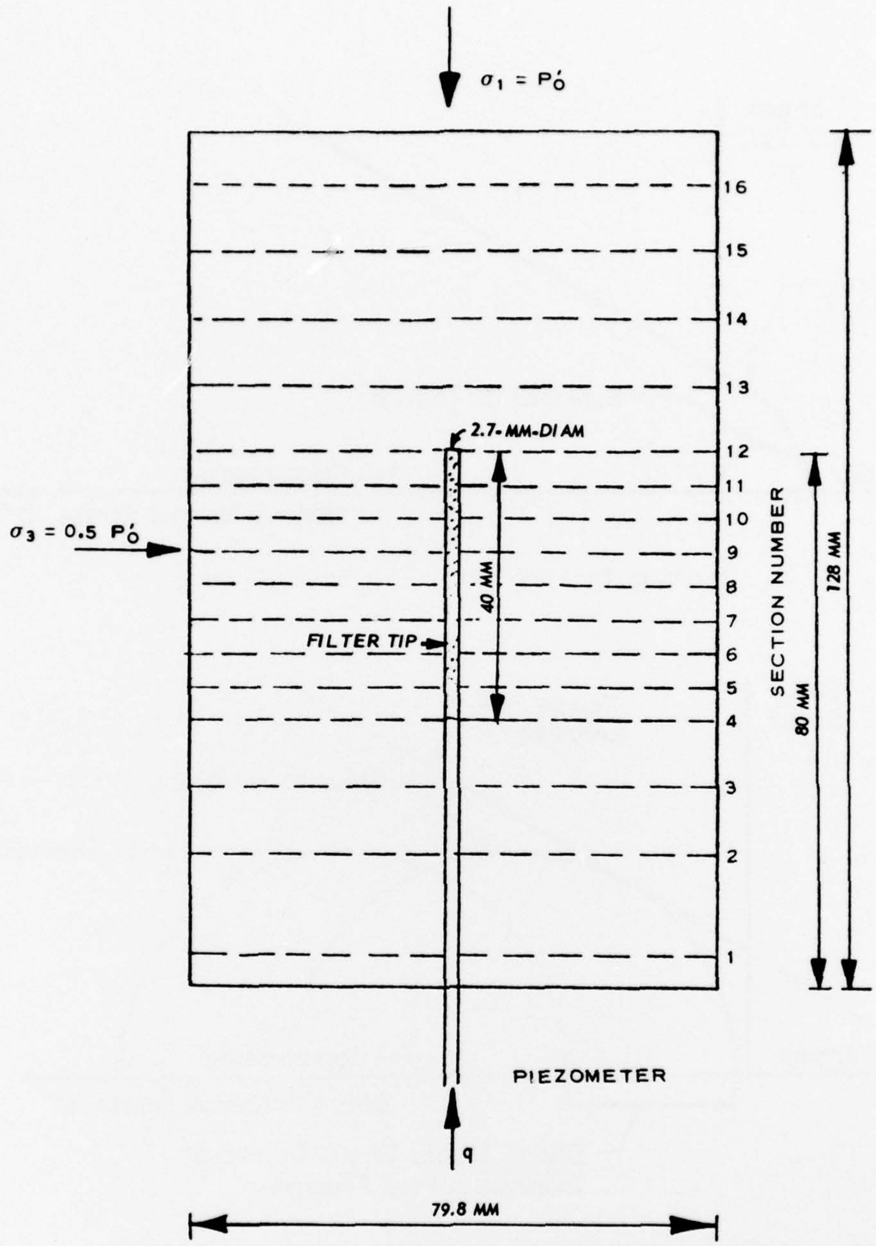


Figure 4. Simulation of the field test in the laboratory (from Reference 7)

Tensile Strength of the Soil by Other Methods

16. Numerous other methods for determining the tensile strength of materials exist,[17] but most are for materials with very high moduli such as rock, concrete, etc., and not soil samples. A device used for testing hollow cylinder soil samples (Figure 5) has been developed at the U. S. Army Engineer Waterways Experiment Station (WES) and a comparison study[18] of tensile strength using two other conventional devices has been conducted. The hollow cylinder device uses a hollow specimen encased by membranes on the inside and outside so that differential pressures across the specimen can be applied. Three hydraulic sources are used to (a) saturate the specimen, (b) apply pressure on the outside of the specimen, and (c) apply pressure to the inside of the specimen. The device is capable of measuring volume and pore pressure change in the specimen and changes in the length of the inside and outside radii. Failure is assumed to be when sudden large changes occur in the radii as defined by the theoretical failure of a thick-wall cylinder. From these deformations tensile strength is determined. Values of tensile strength were determined to be approximately 0.2 to 0.6 kg/cm^2 for the clay soils tested. Relating these values to hydrostatic pressure as mentioned above suggests that the tensile strength could be as much as 18 percent of the water pressure. This procedure does not involve pure hydraulic fracturing by water flow through the specimen but by pressure being transmitted through the membrane.

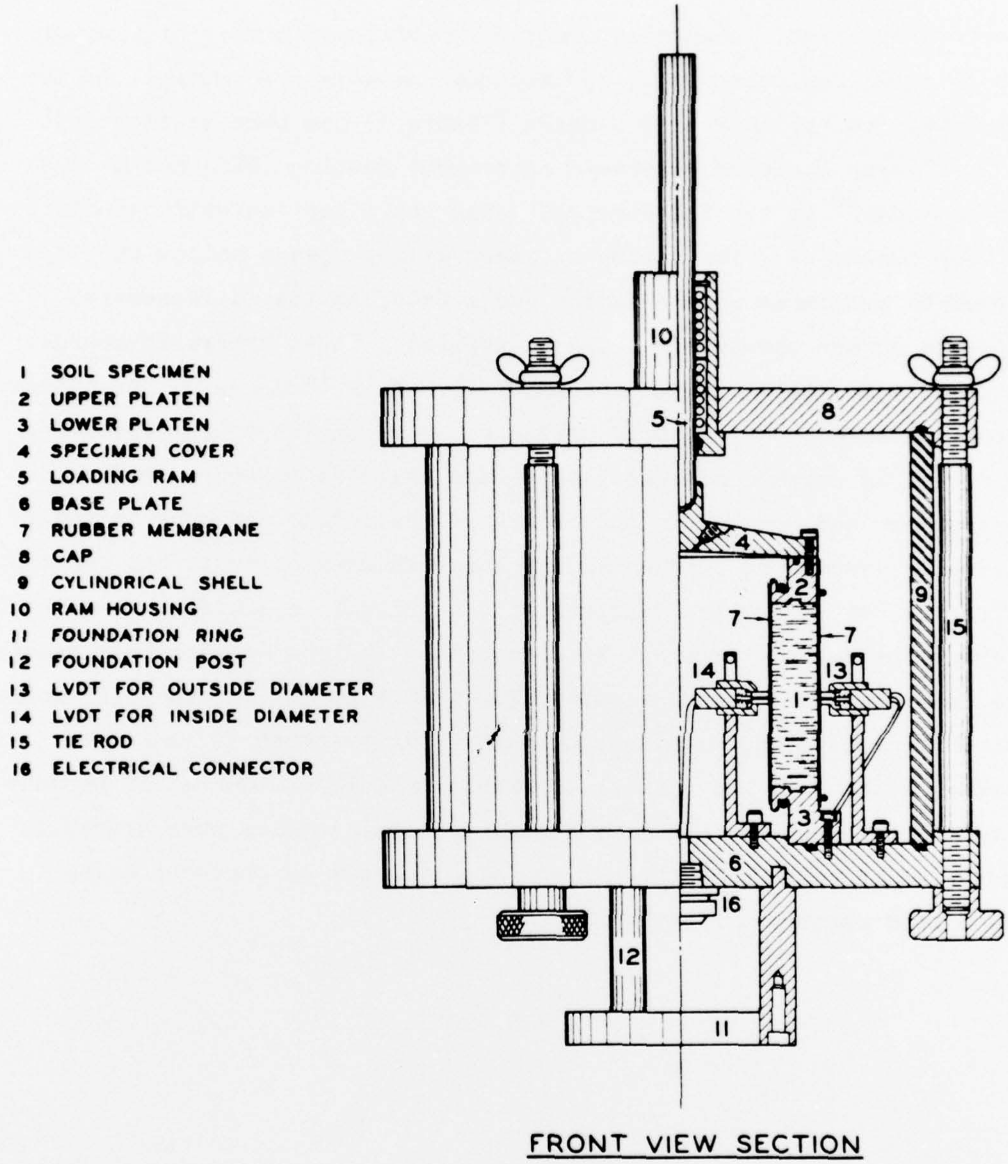


Figure 5. The WES hollow cylinder apparatus (from Reference 18)

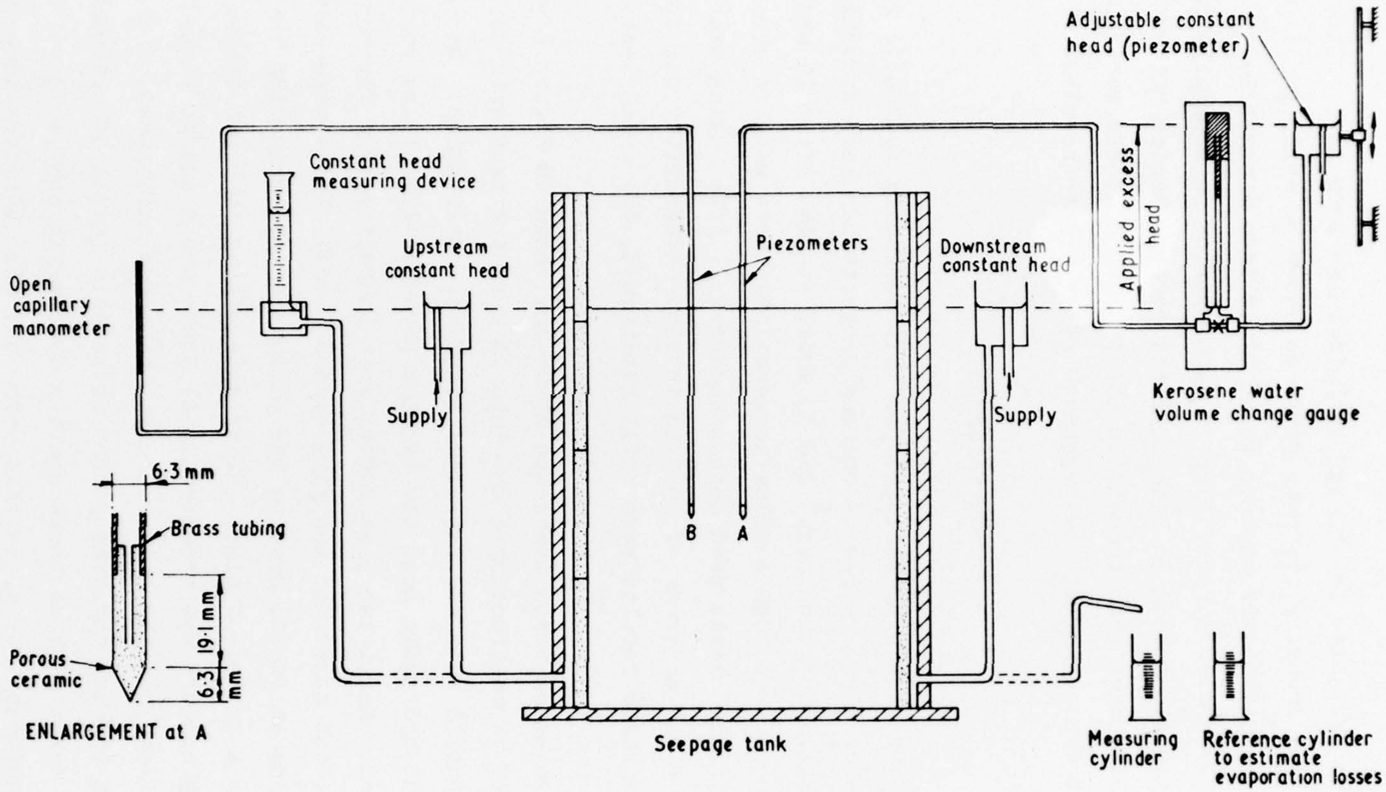
PART IV: FIELD IN SITU TECHNIQUES

17. The hydraulic fracturing technique has been used in the field by the petroleum industry for many years as shown by early publications.[19,20] Mainly it was used to force fluid into a borehole and not as a tool to determine stress. The in situ outflow permeability test has been an important tool in both soil and rock mechanics but not until recently has the fact been brought to the attention of the geotechnical engineer that fracturing at low pressures might negate results.

Model Tests

18. After reviewing failures possibly caused by hydraulic fracturing a more critical review of ongoing projects has been undertaken in recent years. One such case[5] led to model studies after it was concluded that more than 1000 outflow permeability tests were in error due to excess hydraulic heads used during the tests. After using smaller heads in the field an error of 10^{-3} in in situ permeability was determined. Since these results were still questioned, the model tests were conducted.

19. The model tests mentioned above and shown in Figure 6 were carried out by reconstructing a specimen in a square tank with porous stones in opposite ends and two clear sides for observation. By using a differential hydraulic head the overall permeability of the specimen was determined. Next, two piezometers were installed, one for monitoring pressure, the other for applying excess heads. Tests were carried out by applying an excess head to the piezometer and measuring the inflow rate for a period of time. After determining that conditions were stable, the procedure was repeated until there was a sudden marked increase of inflow into the soil. If this head was maintained, a crack could be seen through the transparent sides as a result of hydraulic fracturing. Tests such as these confirm fracturing and yield values not only of permeability as in this case, but also stresses comparable to field conditions.



Courtesy of Geotechnique[5]

Figure 6. Tank for model tests (from Reference 5)

Bjerrum and Anderson Tests[7]

20. As mentioned earlier, lateral stress is an important design parameter and was the basic soil parameter determined by Bjerrum and Anderson[7] in field tests based on the hydraulic fracturing technique. Using the apparatus shown in Figure 7, tests were conducted by forcing

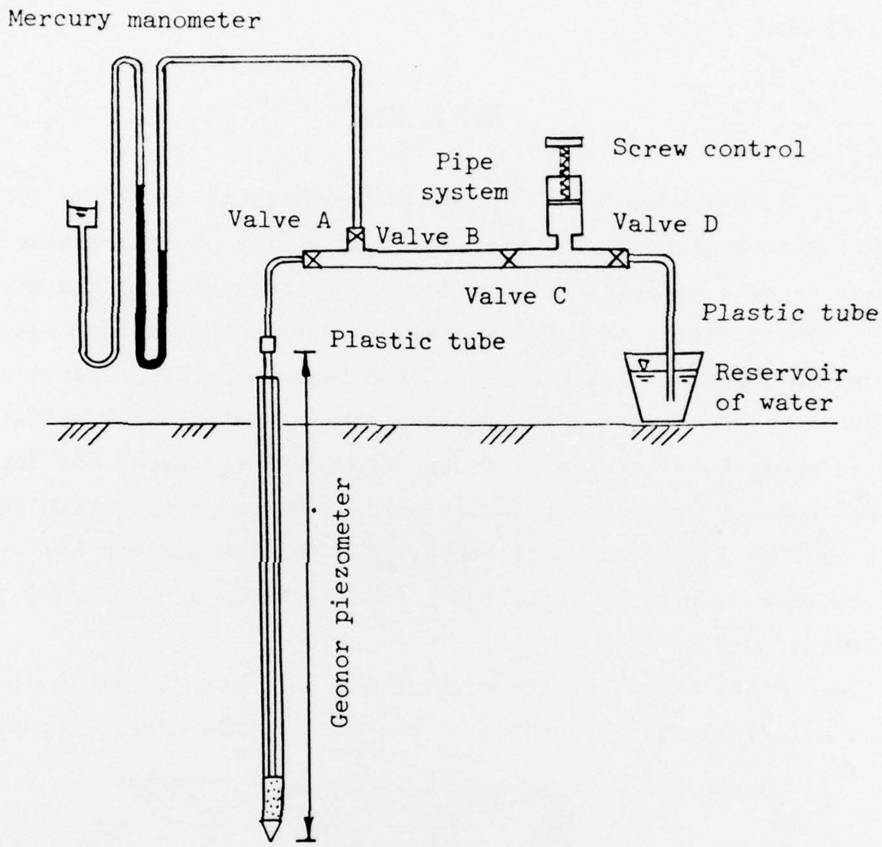


Figure 7. Sketch of the field apparatus (from Reference 7)

a piezometer into the soil and then allowing the water level and stress disturbances to stabilize a length of time dependent on the type of soil. Next a device was attached to the piezometer which consisted of a manometer used for pressure readings, a screw control for forced fluid input, and an open tube to a fluid reservoir. Fluid was forced into the

piezometer at a constant rate until the pressure stabilized. At this point the inward flow was stopped and essentially a falling head test was conducted. Pressure versus time was recorded well beyond a sudden decrease in pressure associated with fracture closure. The flow as a function of pressure was calculated from this data and plotted as shown in Figure 1; the point in time where the sudden drop in pressure occurred is readily discernable. This value should be equal to the total stress at that point.

WES Tests

21. Numerous tests[5,7,21] have been conducted using the hydraulic fracturing technique showing that the possibility of determining stresses in situ is feasible. To develop this capability the WES conducted several field tests using a simple device that incorporates air pressure to maintain flow. Although the parameters of pressure and flow were not refined, the results of the tests indicated minor principal stresses could be determined. Tests were conducted using the "crack closing" concept where the pressure reading corresponding with an abrupt change in flow indicates total stress in a hole or piezometer. Values obtained were determined to be equal to the overburden pressure for an overconsolidated soil ($\sigma_h > \sigma_v$).

22. After obtaining these results a more sophisticated device (Figure 8), similar in principal to one used by the Atomic Energy

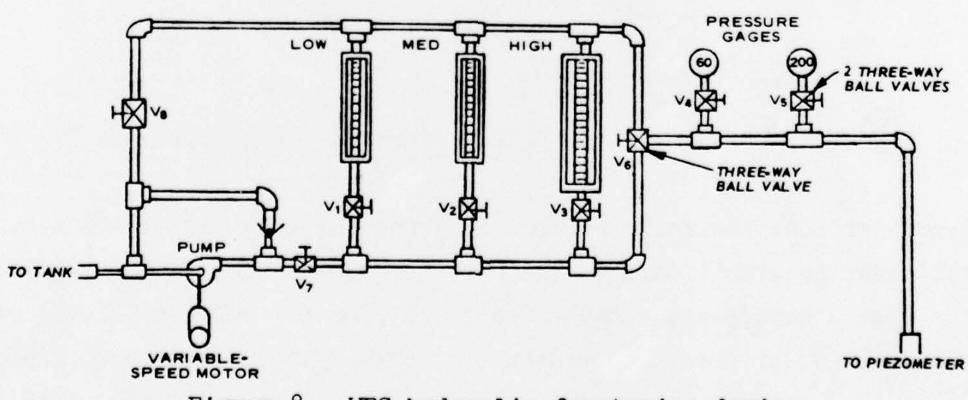


Figure 8. WES hydraulic fracturing device

Commission,[21] was constructed. A pump, operated by a variable-speed electric motor, was used to supply constant flow rates from any water reservoir. Turbine flowmeters and pressure gages were used to measure the parameters needed, flow and pressure. Capabilities include a pressure range of 0 to 1379 kN/m^2 with flow rates of 0 to 189.7 cm^3/sec which is sufficient for most engineering applications in earth dams and in situ investigations where impervious soil is present. The device performed satisfactorily in the initial tests but work was terminated due to project termination.

PART V: CONCLUSIONS AND RECOMMENDATIONS

23. In certain laboratory tests[5] it has been concluded that the closure pressure is the value of the minor principal stress but there is evidence that this may not be true. Hydraulic fracture tests performed and written up by Penman[22,23] suggest that results from total pressure cells in the clay core of a dam are less than the closure pressure obtained by fracturing. It is suggested that orientation of the horizontal features built into the clay by placement and compaction is the reason for the higher fracturing values.

24. Also Massarsch et al.[24] advise the use of considerable caution after a review of their tests using total pressure cells and hydraulic fracturing to determine lateral earth pressures. Even in homogeneous soils the lack of agreement was large and therefore, a range for K_o was felt to be the major contribution of hydraulic fracturing results for use in geotechnical analyses. The overall consensus of the In Situ Measurement Conference[25] seems to be that all in situ tests including hydraulic fracturing have their place but that the results might only be a range of values and caution should be used as each has its limitations.

Conclusions

25. Based on this study the following conclusions are presented:

<u>a</u>. Theoretical considerations have, in general, been proven valid by the laboratory and field tests undertaken by several different groups. Defining stress conditions when the soil fractures is quite difficult but the "crack closing" stress appears much simpler to qualitatively define and determine.

<u>b</u>. A range of existing lateral or minor principal stresses in normally consolidated clays ($K_o < 1$) can be determined using the hydraulic fracturing technique as developed and tested. By assuming the stress measured is lateral stress and by approximating vertical stress an approximation of K_o can be determined.

<u>c</u>. Total stress needed to fracture the soil as measured by

hydraulic fracturing can be applied as check data for permeability and allowable grouting pressure tests. Total stress is the value determined by the fracture test whether it be vertical or lateral direction.

d. Laboratory tests using the fracturing technique yield an acceptable value of tensile strength of the soil. It is believed to be pure tension since no shear failure or plastic flow has been experienced in the tests.

e. Hydraulic fracturing is a useful index tool and can be used on projects where fine-grained soils are involved.

Recommendations

26. Hydraulic fracturing in its present state of development is recognized[25] as a tool to determine a range of in situ stresses. As a fairly inexpensive tool, it is recommended that it be incorporated in the total site investigation programs for cohesive materials. The data obtained can be a useful adjunct to laboratory and in situ testing in design and for evaluating performance of structures during and after construction. The fracturing technique when used in conjunction with grouting and permeability programs in cohesive soils would facilitate determination of allowable pressures.

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APPENDIX A: NOTATION

a	Radius of the cavity, L
b	Width of crack, L
E	Young's modulus, F/L^2
K_o	Ratio of horizontal to vertical stress
L	Length of crack, L
N	Ratio of radial to circumferential effective stress at plastic yield
P'_o	Effective overburden pressure, F/L^2
P'_t	Maximum tensile effective stress, F/L^2
q_c	Rate of flow, L^3/T
r	Radius, L
u_b, u_c	Excess head, F/L^2
u_p	Total pore pressure, F/L^2
α	Factor dependent on soil compressibility
β	Factor dependent on soil compressibility
ν	Poisson's ratio
μ	Displacement, L
μ_v	Viscosity of a liquid, L^2/T
σ	Total stress, F/L^2
σ'	Effective stress, F/L^2
σ_h	Horizontal stress, F/L^2
σ_r	Radial stress, F/L^2
σ'_r, μ_b	Effective radial stress, F/L^2
σ_v	Vertical stress, F/L^2
σ_θ	Circumferential stress, F/L^2
σ'_θ, μ_c	Effective circumferential stress, F/L^2
σ_3	Total stress across a crack, F/L^2
ϕ'	Angle of shearing resistance, radians

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